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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

# LES-5 TRIPLEXER

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## ABSTRACT

This report describes the triplexer used in the UHF communications satellite LES-5. The triplexer is a four-port passive microwave structure which provides a common antenna port for simultaneous operation at the transmit, telemetry, and radio-frequency interference/receive frequencies, and consists of three interdigital band-pass filters connected by appropriate lengths of transmission line.



Accepted for the Air Force
Franklin C. Hudson
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# LES-5 TRIPLEXER

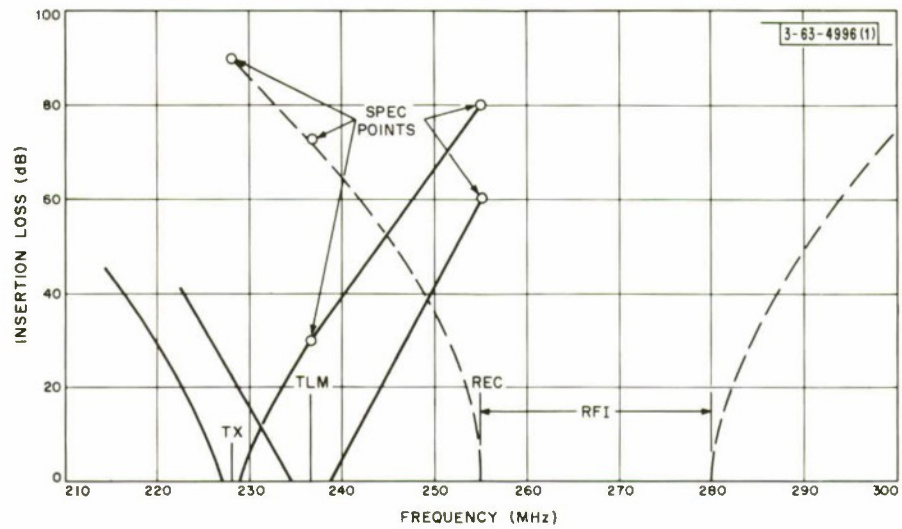
## I. INTRODUCTION

This report describes the design, construction, and testing of the triplexer used in the UHF communications satellite LES-5. The triplexer is a four-port passive microwave structure which provides a common antenna port for simultaneous operation at the transmit (TX), telemetry (TLM), and radio-frequency interference/receive (RFI/REC) frequencies [see Figs. 1(a) and (b)], and consists of three band-pass filters connected by appropriate lengths of transmission line. The TX and TLM filters have narrow bandwidths (approximately 1 MHz), while the RFI/REC filter operates over a 25-MHz bandwidth. All the band-pass filters use quarter-wave interdigital-type resonators and were designed from the low-pass prototype.[1]

Because of the resultant reduction in antenna system complexity, a common antenna terminal for the TX, RFI/REC, and TLM signals was considered highly desirable. However, this places the burden of signal separation on the triplexer system alone. The constraints on the triplexer are such that the transmit frequency and any spurious outputs must be severely attenuated (≈80 dB) before reaching the receiver. For maximum efficiency, the REC, TLM, and TX filters must also have a minimum pass-band attenuation (≈0.5 dB). In addition, the RFI filter bandwidth must have a sufficiently low loss across its pass band so that meaningful measurements can be performed. The basic filter specifications were derived from these and other similar considerations and are shown in Fig. 1(a), along with a block diagram of the system [Fig. 1(b)].

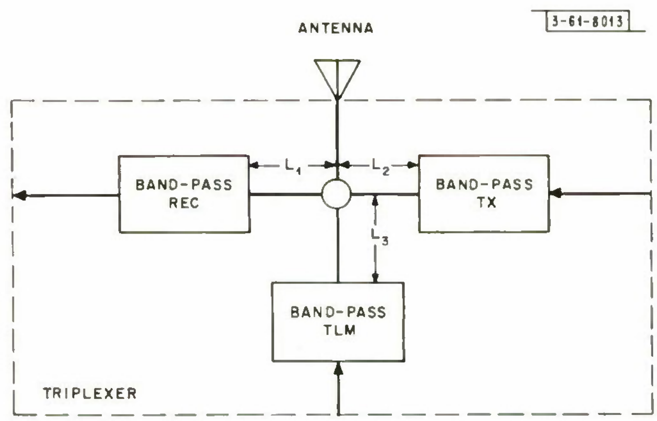
## II. BAND-PASS FILTERS' DESIGN AND MEASUREMENTS

The physical realization of the low-pass prototype designed filters can take the form of either the TEM mode coaxial cavity or a waveguide mode cavity. UHF applications prohibit the use of waveguide construction because of the large sizes necessary at these wavelengths. Coaxial or stripline/slabline TEM mode filters, using either separate cavities aperture coupled or resonators parallel coupled, are suitable UHF designs. However, the parallel-coupling approach is the more compact and simple to design of the two. Initially, the parallel coupled comb-line and interdigital configurations were both considered. The comb-line filter consists of TEM line elements $\sim\frac{1}{8}$ wavelength long and short-circuited at the same end, while the interdigital filter consists of TEM line elements $\sim\frac{1}{4}$ wavelength long and short-circuited at alternate ends. The resonant elements of these filters use capacitive loading at the open ends, both for resonating the lines and for fine tuning. The interdigital filter was chosen since it was felt that it would be more difficult to construct a comb-line filter with a sufficiently high Q because of its need for a larger value of capacitive loading. Each interdigital filter was then designed to satisfy the loss specifications with




| FILTER | APPROXIMATE CENTER FREQUENCY (MHz) | BANDWIDTH (MHz) | INSERTION LOSS (dB) | VSWR |
|---|---|---|---|---|
| TX | 230 | ±0.25 | ~0.5 | ~1.10 |
| TLM | 235 | ±0.25 | ~0.5 | ~1.10 |
| REC | 266 | 255 to 280 | ~0.5 at REC | ~1.10 at REC |

(a)




(b)

Fig. 1. LES-5 triplexer: (a) design specifications; (b) triplexer configuration.

a minimum size package. Several designs were calculated, using both equal-element and Chebyshev configurations, varying the number of elements (n) and the stripline plate spacing. The best compromise design was selected which achieves low pass-band loss and still meets the stop-band requirements for the minimum number of elements.

The conventional method of coupling into and out of an interdigital filter utilizes two additional elements. A method of direct tapped coupling without using any extra elements was used in the design of all the band-pass filters. An approximate tap position was determined using available formulas[2]; however, the final position was determined experimentally by adjusting for the best impedance match at the frequency of interest. The final tap position was within 20 percent of that predicted by calculation.

### A. Transmit (TX) and Telemetry (TLM) Band-Pass Filters

Since the TX and TLM filter requirements are similar, it was decided that both filters should have the same basic design. Calculations of several Chebyshev and equal-element configurations showed that the lowest pass-band loss and best rejection characteristics would be achievable with an $n = 5$ equal-element design.[3,4] A further improvement upon the design of these filters was subsequently made by slightly increasing the loaded Q ($Q_L$) of the center resonant element (reducing its diameter). The pass-band ripple was reduced appreciably by this change, with an accompanying improvement in skirt selectivity.[5] Figures 2(a) and (b) show plots of both the TLM and TX band-pass filter measured data, respectively.

### B. Receive (REC) Band-Pass Filter

An investigation similar to that carried out in the filter designs mentioned above revealed that the most optimum design for the RFI/REC filter was a 7-element Chebyshev with a ripple factor of 0.1 dB. The REC frequency is positioned in the first null at the edge of the RFI pass band (see Fig. 3), thus increasing the out-of-band rejection characteristics. The triplexer measured characteristics [shown in Fig. 4(c)] show an increasing loss at the higher RFI frequencies because the triplexer configuration uses a relatively long line length from the telemetry filter to transform both TX and REC open-circuit impedances to the common junction. Above the REC frequency, the transferred impedances begin to shunt the junction, with the result that the pass-band loss increases at the shorter wavelengths.

Typical design calculations for the RFI/REC band-pass filter are described in the Appendix. Figure 3 is a plot of the measured data and also shows the calculated response.

The most critical values to establish in these band-pass filters are the interelement couplings. Prototype filters were constructed to enable one to adjust the positioning of the resonating elements and thereby control the couplings. A technique[6] for measuring the adjacent element coupling was used which necessitated measuring the fractional bandwidth between primary response peaks. The fractional bandwidth is related to the coefficient of coupling between two resonators. In general, it was found that only if the deviation from the calculated coefficient of coupling was $<2$ percent could the 7-element Chebyshev filter be tuned correctly. The equal-element filter (TX and TLM) adjustments were not as critical.

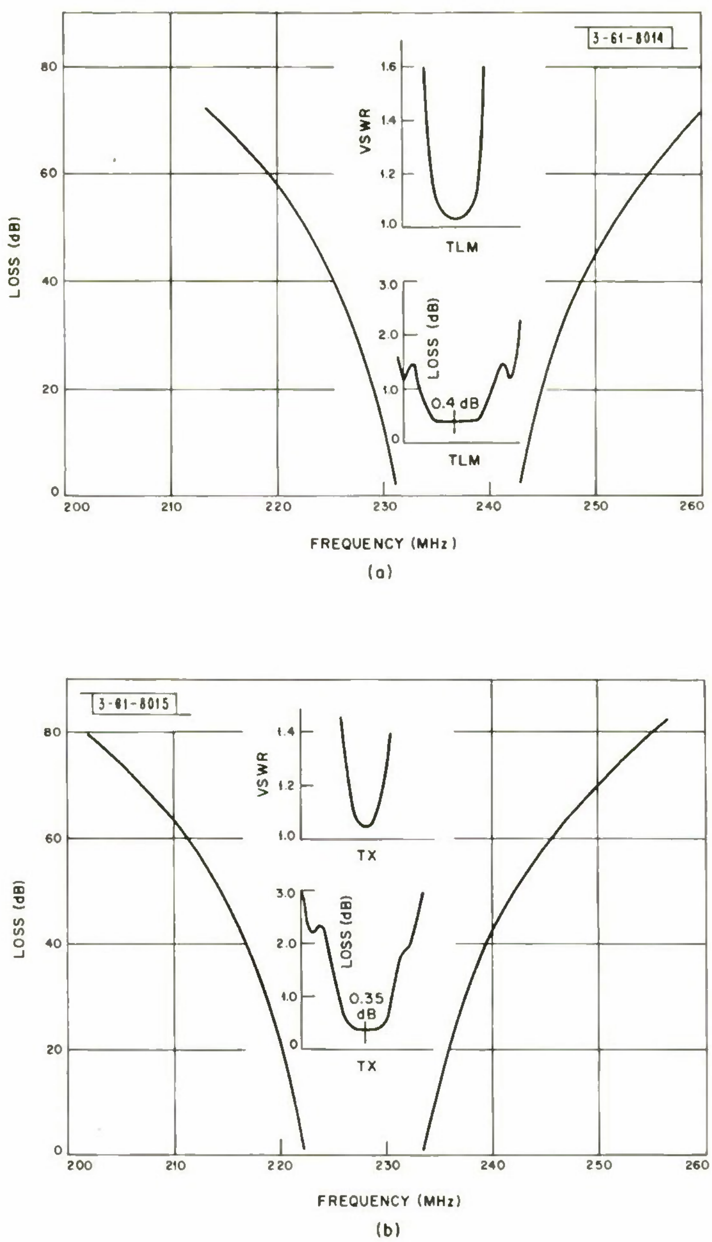



Fig. 2. Measured data of (a) TLM and (b) TX band-pass filters.

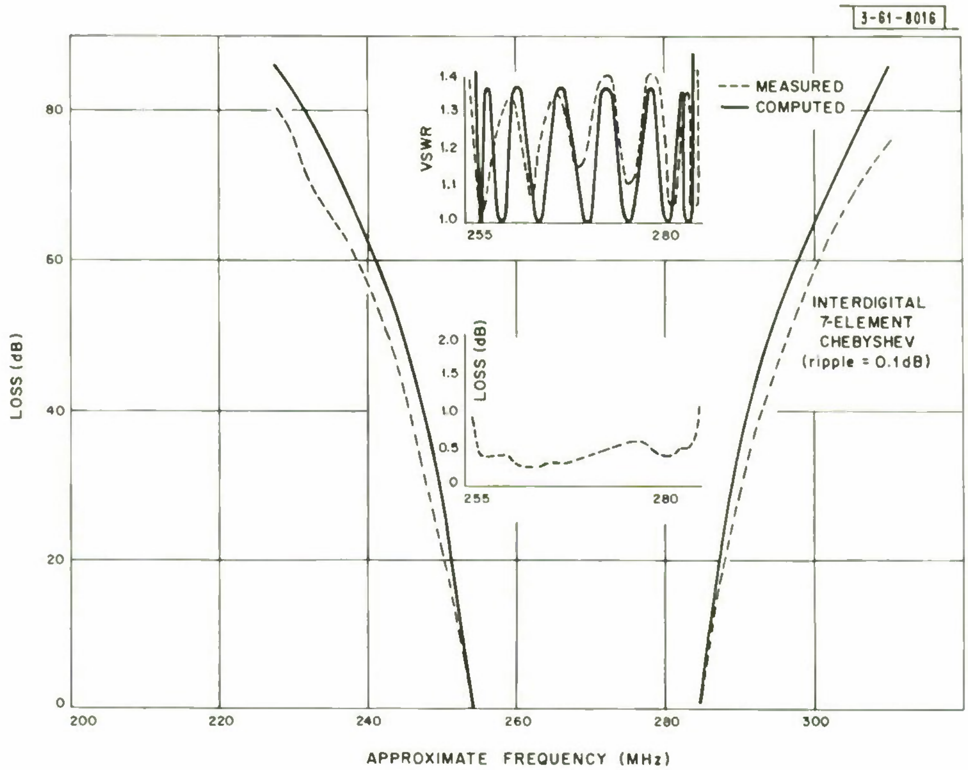
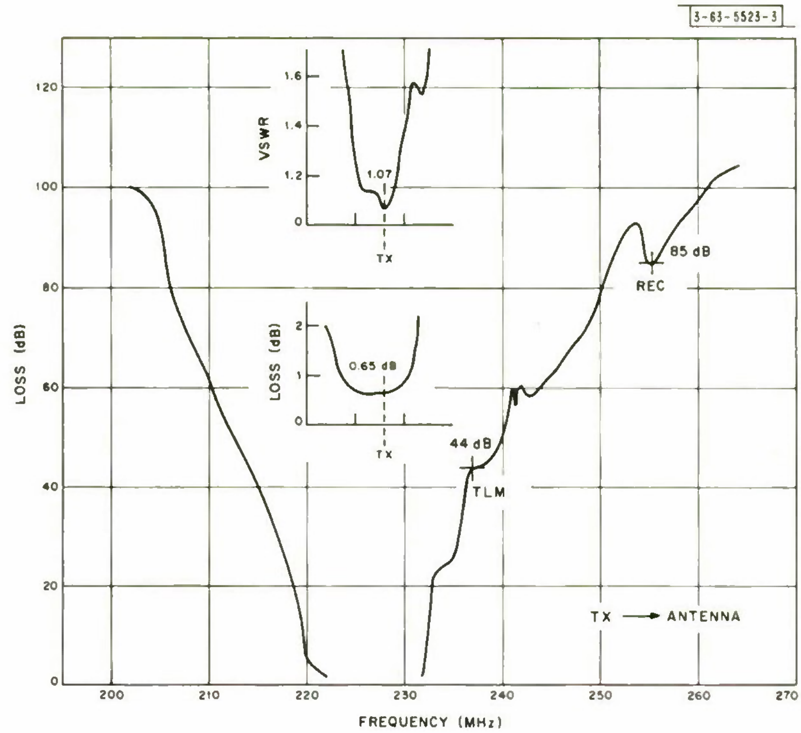



Fig. 3. RFI/REC band-pass filter.

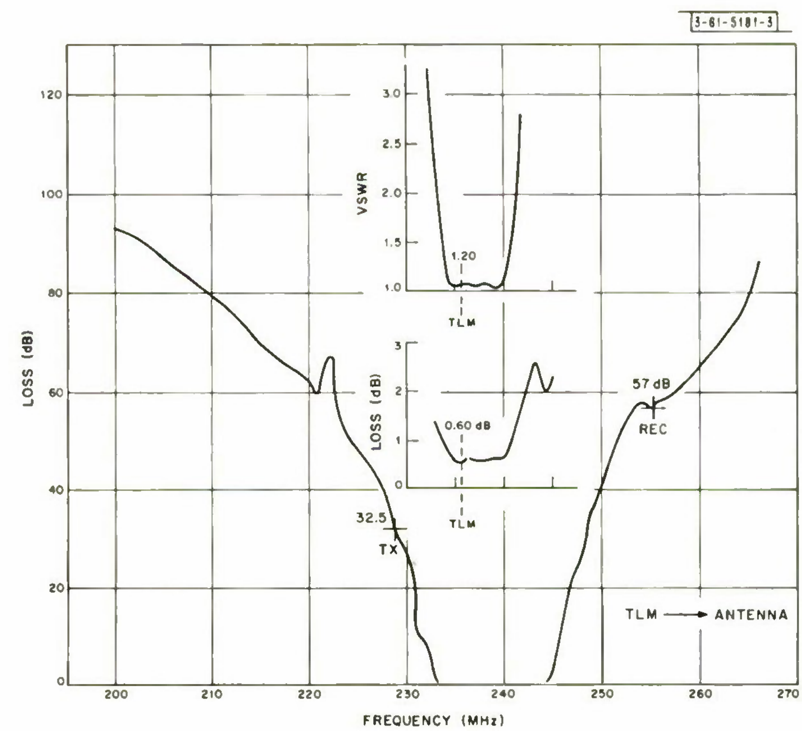
## III. TRIPLEXER

### A. Design and Performance

A triplexer configuration is formed when three band-pass filters are combined through a common junction such that with simultaneous operation the overall response of each filter is relatively unaffected. In general, multiplexer designs are categorized into two types: contiguous and noncontiguous. Contiguous refers to those multiplexers that have no guard bands separating the pass bands, while the noncontiguous multiplexer does have guard bands separating the pass bands. The design of the contiguous class of multiplexers would be more complex than the non-contiguous because the interaction between filters would require additional compensation if one were to achieve a good impedance match at the input of a properly terminated multiplexer. Since the LES-5 multiplexer does have guard bands between the TX, TLM, and REC channels, the design procedure of combining the basic band-pass filters by using appropriate line lengths tied to a common junction is the most straightforward approach; then each filter can be adjusted separately, simplifying the tuning procedure [this was depicted in Fig. 1(b)]. Since the entire bandwidth of 25 MHz through the RFI/REC filter was expected to be somewhat degraded due to interaction effects, the approach was used to optimize the TX, TLM, and REC frequencies for the triplexer operation and accept the resultant RFI pass-band loss. The very high rejection (~80 dB) to the TX frequency presented by the RFI/REC filter is very nearly an open circuit at the reject frequency. By adjusting the line lengths $L_1$, $L_2$, and $L_3$ [see Fig. 1(b)], the approximate open-circuit impedances of each filter at the critical reject frequencies were transformed to the common junction. Line length $L_1$ transformed the REC filter input impedance, and line length $L_2$ transformed the TX filter input impedance to the common junction. When the TLM filter is




(a) TX filter – loss and VSWR vs frequency.




(b) TLM filter – loss and VSWR vs frequency.

Fig. 4(a–c). Measured response curves of flight-model triplexer 2 for LES-5

added to the junction, line length $L_3$ must transform both TX and REC impedances such that both appear as an open circuit at the junction. The finalized line lengths were:

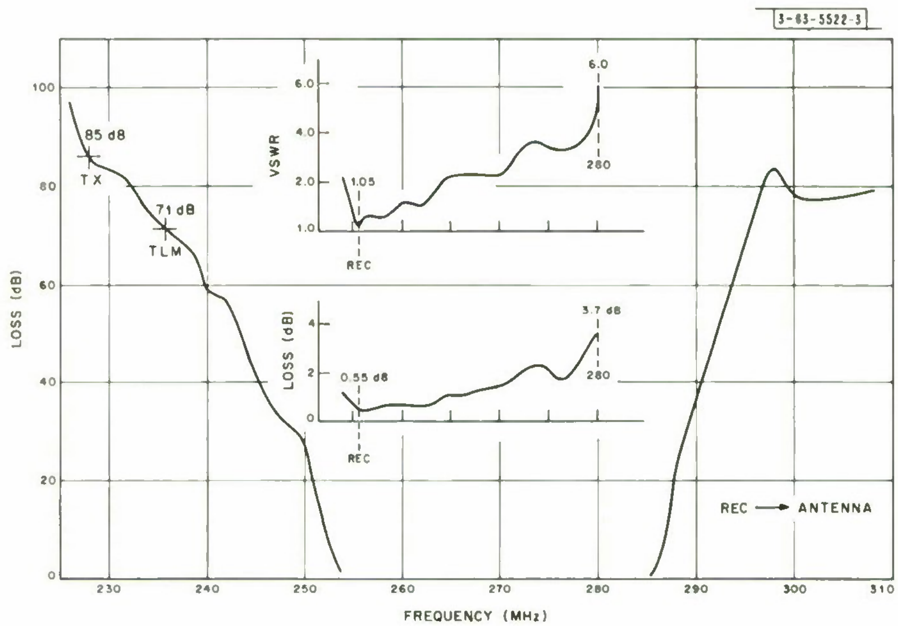
$$L_1 = 6\frac{3}{4} \text{ inches}$$

$$L_2 = 3\frac{15}{16} \text{ inches}$$

$$L_3 = 38\frac{1}{4} \text{ inches.}$$

The junction is a copper-plated gold-flashed aluminum box into which 0.141 semi-rigid coaxial cables are inserted and then soldered together. Special connectors are used consisting of the 0.141 cable outer conductor split four ways then laid flat and soldered to the box. The cable is then firmly held in place with a flange. This technique was used to allow for easier adjustment of the cable lengths at the junction. Figures 4(a) through (c) show the measured response curves of the triplexer. All the triplexer measured response curves show some variations from the smooth response curves of the single filters due to interaction effects between filters, through the triplexer junction. Although the individual RFI/REC filter response curve depicted in Fig. 3 exhibits an 80-dB rejection at the TX frequency, the measured triplexer response shows that the 85-dB specification has been met. The interaction effects through the junction have evidently increased the rejection in this area. The reason for the sloping RFI pass-band loss was discussed in Sec. II-B.

All the filters are of aluminum construction, copper plated and then gold flashed to reduce the dissipative insertion loss of the filters and to provide corrosion protection. Good contact at the short-circuited ends of the resonant rods was obtained by dip brazing the rod ends to $\frac{7}{8}$-inch-diameter cylinders which were then press-fit into the aluminum cavity walls. These cylinders were then electron-beam welded in place. The TX, TLM, and RFI/REC band-pass




(c) RFI/REC filter – loss and VSWR vs frequency.

Fig. 4. Continued.

filters are then assembled into a flight package and initially combined with the two band-stop filters mounted on top. However, the flight model did not use the band-stop filters. All the filter inputs and outputs are "TNC"-type chassis connectors with the center conductors soldered directly to the input and output resonator rods. The band-pass filters are tuned at each resonator rod end by adjusting a disk-type capacitor. The three band-pass filters assembled into triplexer form weigh 7 lb 14 oz. Figure 5 is a photograph of the triplexer showing the output connectors, the common junction, and interconnecting lines.

### B. Environmental Tests

The measured performance of the triplexer was unaffected by the various shock and vibration tests which were carried out to both simulate and exceed the expected spacecraft environment.

The triplexer was also subjected to temperature cycling of $-40\,^{\circ}C$ to $+60\,^{\circ}C$. During the entire temperature-cycling run of approximately two-days duration, the triplexer characteristics such as VSWR, insertion loss, and out-of-band rejection were continuously monitored, resulting in no measurable deviation from the normal room-temperature operation of the triplexer.

### C. High-Power Tests

The TX filter by itself had been successfully tested at the rated power (40 W CW) under atmospheric conditions. However, when the unit was tested in a vacuum of approximately $10^{-6}$ mm of Hg, an RF voltage breakdown was observed at an input power level of approximately 8 W. To assist in determining the reason for the failure, the filter cover was replaced with a fine-mesh screen enabling one to view the resonating rods and any evidence of the breakdown. The filter was placed in a vacuum bell jar system at a pressure of approximately $10^{-6}$ mm of Hg. The input, reflected, and output powers of the filter were monitored, then power was increased gradually until at about 8-W input the reflected power increased drastically and the output power dropped to nearly zero, indicating a catastrophic breakdown. Simultaneously, a bluish glow was observed between the resonating elements and the top and bottom surfaces of the filter. At

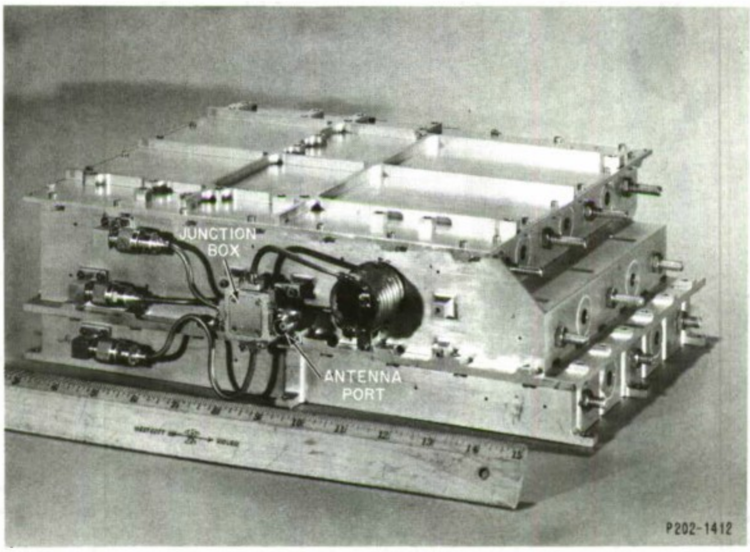


Fig. 5. LES-5 triplexer.

this low pressure, the only breakdown that could exist would be the result of a secondary emission resonance phenomenon (multipactor) which also can ionize residual gases that still remain on the surface of the filter and further complicates any analysis of the phenomenon. The ionization of these gases was the bluish glow that was observed. Secondary emission between two surfaces can occur when free electrons are accelerated from one surface through an RF field and bombard the other surface with sufficient energy to release more electrons (see Ref. 7 for detailed description). When the field reverses and these electrons are allowed to travel at approximately one-half cycle, bombardment of the first surface takes place with the release of more electrons. If the ratio of released to bombarding electrons (secondary emission ratio $\delta$) is $>1$, a cloud of resonating electrons can be generated resulting in detuning of a filter or an actual discharge taking place. The mean free path must be much longer than the plate spacing for this phenomenon to occur. There are several well-known approaches that can be considered in order to eliminate multipactor:

(1) Pressurization. If atmospheric pressure is maintained, the length of the discharge path is then large compared with the mean free path of the electron, and the electron cannot acquire enough energy between collisions to produce secondary electrons.

(2) Foam. The mean free path length is radically lowered when the space is filled with foam, thus destroying the resonance conditions.

(3) Surface Techniques. Surface coatings of sheet teflon tend to raise the initial voltage at which multipactor starts by a factor between one and two times the uncoated value. Any coating or plating that would decrease the secondary emission ratio to $<1$, would also prevent multipactor. However, in order to prevent any degradation in the surface conductivity, exotic plating techniques would need to be investigated with no assurance of early success.

(4) Bias. A DC bias applied between surfaces can prevent multipactor from starting by modifying the initial conditions of the electron trajectory and upsetting the resonance condition.

(5) Geometry. Spacings can be reduced to the point where the conditions of resonance are no longer satisfied.

It was decided that the most attractive solution was to fill the filter with a low-loss, low-dielectric constant foam material. This was the only approach that could be carried out on the completed TX filter without a major design change. An expanded polystyrene foam of approximately $1\frac{1}{4}$ lb/cubic-foot density was used to completely fill the TX filter. This foam has a dielectric constant of 1.02 and a loss tangent of 0.0002. The foam-filled TX filter was retuned because of the slight change in dielectric constant, and the increased pass-band loss due to the foam was measured as less than 0.1 dB. The rest of the response curve was not changed significantly. The filter was again placed in a vacuum, and operated successfully at the rated input power of 40 W. The input power was then increased to 120 W with still no evidence of any breakdown. Although breakdown did eventually occur at 160-W input, it was felt that the 120-W operation (three times the rated power) indicated a reliable safety factor.

## IV. BAND-STOP FILTERS' DESIGN AND MEASUREMENTS

Early transponder system measurements indicated that additional triplexer filtering might be necessary; therefore, two band-stop filters were designed[8] to enhance the rejection characteristics of the TX and REC filters. Although subsequent system tests proved that these filters were not necessary for the final flight version, a general description of their design will be presented.

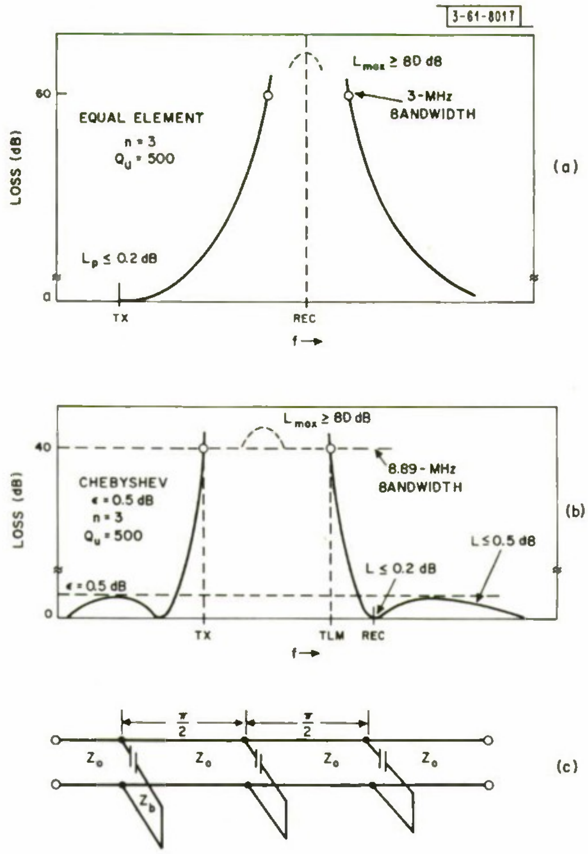



Fig. 6. (a) Band-stop filter response (TX line); (b) band-stop filter (RFI/REC line); (c) circuit arrangement.

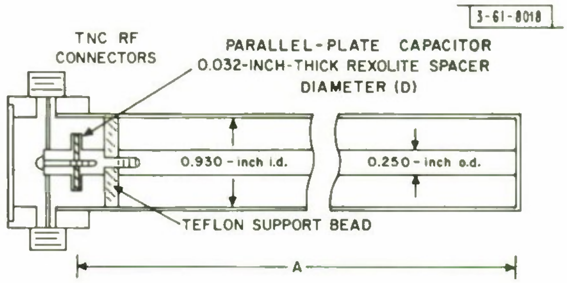
TABLE I

BAND-STOP FILTER LOSS VALUES

| RFI/REC Filter | | |
|---|---|---|
| Frequency | Losses (dB) Computed | Losses (dB) Measured |
| TX | 40 | 44 |
| TLM | 40 | 39 |
| REC | ⩽0.2 | 0.2 |
| **TX Filter** | | |
| REC | ⩾80 | >90 |
| TX | ⩽0.2 | 0.2 |

The RFI/REC band-stop filter was designed for 40-dB rejection at both TX and TLM frequencies, and to pass with low loss the RFI/REC frequencies. A 3-element Chebyshev design with a 0.5-dB maximum pass-band ripple (VSWR 2:1) was selected. The bandwidth of the filter was adjusted to place the REC frequency in the null to achieve best match and minimum REC loss.

The TX band-stop filter was designed to give over 60-dB rejection in a 3-MHz band about the REC frequency. This band stop is an equal-element filter also using 3 elements. All the resonator elements in both filters were of similar construction. As shown in Fig. 6(c), the basic band-stop resonant element is a short-circuited line slightly less than 90° long and resonated with a series capacitor. The resonators are then quarter-wave coupled by lengths of 0.141 semi-rigid line. The computed response curves of each filter are sketched in Figs. 6(a) and (b). Shown are the important loss values. The band-stop filter measured loss values agreed very closely with the theory as shown in Table I. The approximate dimensions of each filter are $2 \times 2 \times 8\frac{1}{2}$ inches. Figure 7 is a sketch of one of the filter elements showing the dimensions used; included is a table listing the critical dimensions for all 6 elements. Deviations between calculated and measured values are probably due to minor effects of the junction discontinuities which were ignored in the design. Figure 8 is a photograph of the RFI/REC band-stop filter showing the various component parts.




| | ELEMENT | CALCULATED VALUES D (inches) | CALCULATED VALUES A (inches) | ACTUAL VALUES D (inches) | ACTUAL VALUES A (inches) |
|---|---|---|---|---|---|
| TX FILTER | 1 | 0.520 | 8.450 | 0.510 | 8.416 |
| | 2 | 0.520 | 8.458 | 0.510 | 8.525 |
| | 3 | 0.520 | 8.450 | 0.510 | 8.431 |
| RFI/REC FILTER | 1 | 0.630 | 8.20 | 0.630 | 8.187 |
| | 2 | 0.568 | 8.90 | 0.568 | 9.156 |
| | 3 | 0.630 | 8.20 | 0.630 | 8.187 |

Fig. 7. Band-stop filter dimensions.

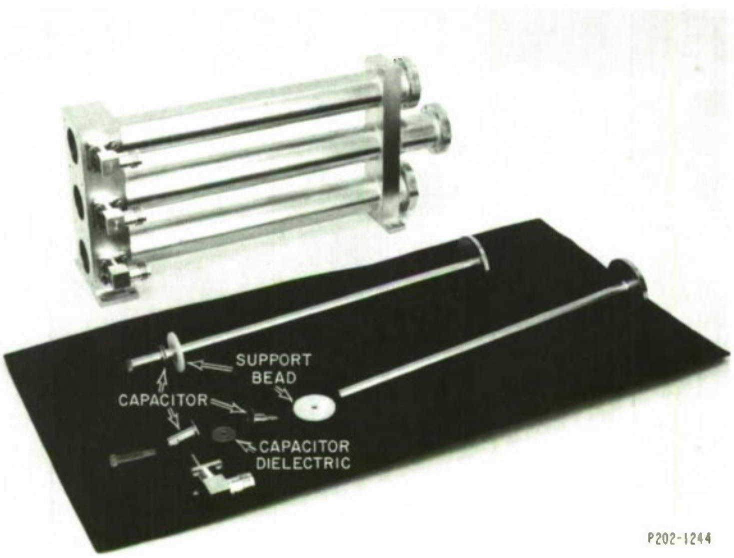



Fig. 8. Exploded view of LES-5 band-stop filter.

## APPENDIX
## TYPICAL DESIGN CALCULATIONS

The required unloaded Q ($Q_u$), the TX and TLM frequencies, and pass-band losses are calculated here for the RFI/REC filter.

Information is available in Refs. 9 and 10 to enable one to readily perform the necessary calculations in order to arrive at the most optimum design. The overall filter size must be determined, and the least number of resonant elements that will result in meeting the stop-band performance requirements must be set. Next, one must consider a choice of pass bandwidth and out-of-band loss. After several such design iterations, one can usually choose a final design that most nearly satisfies all the multiple constraints.

The necessary $Q_u$ can be approximated from the midband dissipative loss ($L_{db}$) formula:

$$L_{db} = 4.34 \frac{\Sigma\, gk}{Q_u W}$$

where

$g_k$ = low-pass prototype element value

$Q_u$ = unloaded Q

W = fractional bandwidth.

The low-pass prototype element values ($g_k$) for Chebyshev filters can be obtained from available tables. Assuming a 7-element filter and a ripple factor of 0.1 dB, these element values are:

$$g_1 = g_7 = 1.1811$$

$$g_2 = g_6 = 1.4228$$

$$g_3 = g_5 = 2.0966$$

$$g_4 = 1.5733.$$

Using a 25-MHz bandwidth (W = 0.0935) and assuming less than a 0.5-dB loss at midband, we have

$$Q_u = \frac{10.974 \times 4.34}{0.5 \times 0.0935} = 1020 \quad .$$

Therefore, an unloaded Q of over 1000 is needed for the values chosen. The filter was designed for a 76-ohm impedance level because minimum loss occurs in a coaxial transmission line at this impedance, and for the stripline it is also expected to be near optimum. The theoretical unloaded Q for a 76-ohm copper coaxial line is given by:

$$Q_u = 3400\, b\sqrt{F}$$

where

b = inner diameter of outer conductor (in inches)

F = frequency (in GHz).

Applying this formula as an approximation to our rod between parallel plate configuration and assuming a plate spacing of 1.250 inches to obtain a standard rod size inner conductor diameter of 7/16 inch, the unloaded Q is then

$$Q_u = 3400 \times 1.25 \times 0.5175 = 2200 \quad .$$

The achievable $Q_u$ will fall somewhat short of the theoretical value due to manufacturing processes – namely, the surface roughness of the structures, the quality of plating, and upon how well mating surfaces are joined. Figure A-1 depicts the band-pass filter response and some parameters necessary for the filter design. Assuming the bandwidth specification of 25 MHz, the normalized TX frequency ($\omega_{TX}$) is calculated:

$$\omega_{TX} = \frac{(f_{TX}/f_o) - (f_o/f_{TX})}{W} = \frac{1.171 - 0.85}{0.0935} = 3.38 \quad .$$

Referring to the available curves of Ref. 10, the loss is ~92 dB at $\omega_{TX} = 3.38$ for a 7-element Chebyshev 0.1-dB ripple design. This can also be calculated more exactly using the equation for the stop-band loss ($A_{db}$) for a Chebyshev response low-pass filter:

$$A = 10 \log_{10} \{1 + [(A_m/10^{10}) - 1] \cosh^2 (n \cosh^{-1} \omega)\} \quad , \qquad \omega \geqslant 1$$

where

$A_m$ = ripple (in decibels) of pass band = 0.1 dB

n = number of elements

W = fractional bandwidth

$\omega$ = a normalized frequency variable = $\dfrac{|(f/f_o) - (f_o/f)|}{W}$

connecting the low- to band-pass transformation. Previous tests had indicated that when this filter is used in the triplexer the bandwidth would tend to narrow somewhat and the out-of-band losses would probably increase. Consequently, the design bandwidth was extended to W = 0.109 where $\omega_{TX} = 3.05$, resulting in a TX reject loss of 86.4 dB. The rejection at the TLM frequency with $\omega = 2.36$ is now calculated as 69.25 dB. Calculating the expected midband dissipative loss,

$$L_{db} \approx 4.34 \frac{\Sigma\, gk}{Q_u W} = 4.34 \frac{10.974}{1320 \times 0.109} = 0.33 \text{ dB} \quad .$$

Since the calculated midband loss is less than 0.5 dB, and both TX and TLM rejection losses are acceptable, one can proceed with the design.

The coupling coefficients $k_{i,i+1}$ between the resonators are found from the formula

$$k_{i,i+1} \neq \frac{W}{\sqrt{g_i g_{i+1}}}$$

$$k_{1,2} = k_{6,7} = 0.08485$$

$$k_{2,3} = k_{5,6} = 0.06369$$

$$k_{3,4} = k_{4,5} = 0.06057$$

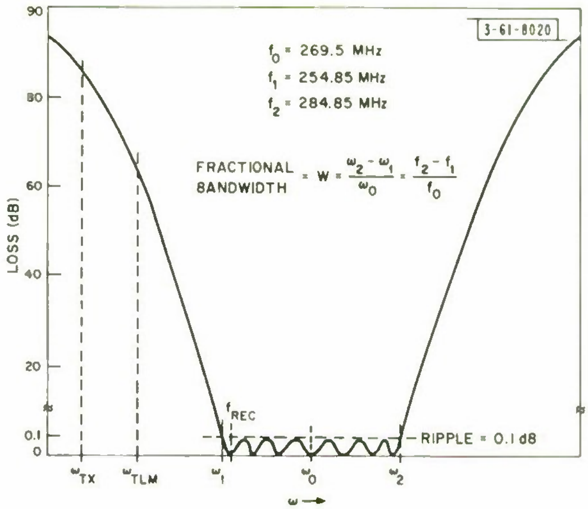



Fig. A-1. Response of 7-element Chebyshev band-pass filter.

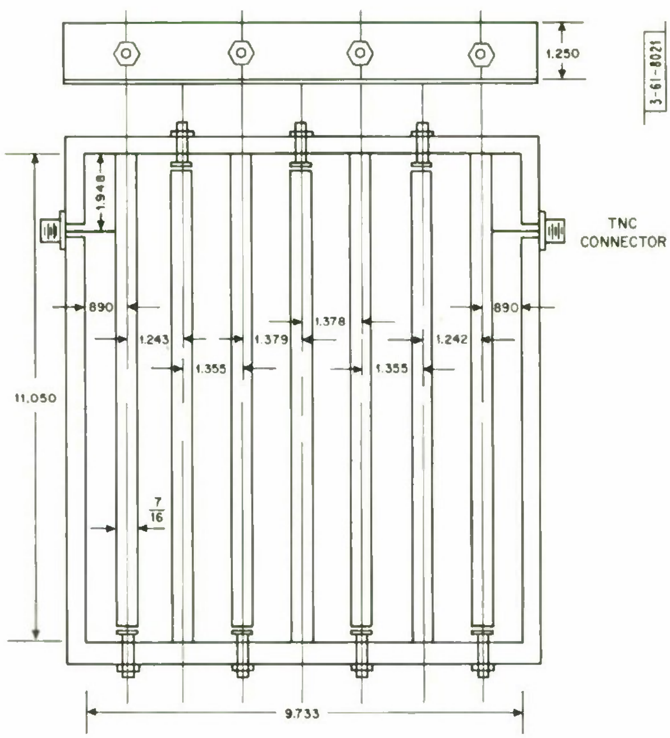



Fig. A-2. RFI/REC band-pass filter dimensions (in inches).

M. Dishal has published interdigital filter design curves[2] which allow one to fix the interelement spacings using the coupling coefficients, the stripline ground-plane spacing, and the diameter of the rod elements. With a rod diameter of 7/16 inch and a ground-plane spacing of 1.250 inches, the interelement spacings (S) are listed:

| Elements | Spacing (inches) |
|---|---|
| $S_{1,2} = S_{6,7}$ | 1.239 |
| $S_{2,3} = S_{5,6}$ | 1.350 |
| $S_{3,4} = S_{4,5}$ | 1.370 |

The final rod spacings actually used after experimental adjustment of the couplings are shown in Fig. A-2. The calculated and measured responses of the filter, showing the excellent agreement obtainable with this type filter design, were depicted in Fig. 3. The falling off in the measured curve of the large out-of-band-loss values is probably due to the neglect of nonadjacent rod couplings and the small bandwidth approximations that are used in the design technique.

ACKNOWLEDGMENT

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13. ABSTRACT

This report describes the triplexer used in the UHF communications satellite LES-5. The triplexer is a four-port passive microwave structure which provides a common antenna port for simultaneous operation at the transmit, telemetry, and radio-frequency interference/receive frequencies, and consists of three interdigital band-pass filters connected by appropriate lengths of transmission line.

14. KEY WORDS

LES
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